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Photometric Monitoring of the Gravitationally Lensed Ultraluminous BAL Quasar APM 08279+5255

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ABSTRACT

We report on one year of photometric monitoring of the ultraluminous BAL quasar APM 08279+5255. The temporal sampling reveals that this gravitationally lensed system has brightened by ∼0.2 mag in 100 days. Two potential causes present themselves; either the variability is intrinsic to the quasar, or it is the result of microlensing by stars in a foreground system. The data is consistent with both hypotheses and further monitoring is required before either case can be conclusively confirmed. We demonstrate, however, that gravitational microlensing can not play a dominant role in explaining the phenomenal properties exhibited by APM 08279+5255. The identification of intrinsic variability, coupled with the simple gravitational lensing configuration, would suggest that APM 08279+5255 is a potential 'golden lens' from which the cosmological parameters can be derived and is worthy of a monitoring program at high spatial resolution.

Subject headings: Quasars: Individual (APM 08279+5255), Gravitational Lensing

1. Introduction

During a survey of carbon stars in the Galactic halo (Totten & Irwin 1998), spectroscopic observations of a stellar candidate revealed it to be a broad absorption line quasar at a redshift of $z \sim 3.9$ (Irwin et al. 1998). With $m_R = 15.2$ this system apparently possesses a luminosity exceeding $10^{15}\,L_\odot$, placing it amongst the most luminous objects currently known. The optical emission is coincident with a bright IRAS source and follow-up observations with Submillimetre

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Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope reveal that a substantial proportion of this emission arises in the sub-mm/IR regime (Lewis et al. 1998). This is characteristic of emission from warm dust and indicates that APM 08279+5255 represents one of the most extreme examples of an ultraluminous infrared galaxy (Sanders & Mirabel 1996).

Analysis of ground-based images, obtained with the 1.0 m Jacobus Kapteyn Telescope on La Palma, revealed that the point spread function of APM 08279+5255 was not stellar, but in fact was better represented by a pair of point-like sources separated by $\sim 0\overset{\prime\prime}{.}4$ (Irwin et al. 1998). Such a configuration is indicative of the action of gravitational lensing. This conclusion was confirmed using adaptive optical imaging at the Canada-France-Hawaii Telescope (Ledoux et al. 1998), as well as images from the 10m Keck telescope (Egami et al. 1999) and NICMOS images from the Hubble Space Telescope (Ibata et al. 1999), that clearly reveal the composite nature of this system. Several gravitational lens models have been derived from these studies, suggesting that the magnification of the quasar source is $\sim 10 - 100$. Even accounting for this substantial magnification, APM 08279+5255 remains amongst the most intrinsically luminous systems currently known. Its apparent brightness, however, has made it an ideal target for several studies of high redshift quasars (Downes et al. 1999; Hines, Schmidt & Smith 1999; Ellison et al. 1999; Ellison et al. 1999a)

In this paper, we too take advantage of the gravitational lensing magnification and present the results of one year of photometric monitoring of this phenomenal object. In Section 2 we outline the observational programme, data reduction technique and results of the monitoring, while in Section 3 we discuss the source of the observed variability. Section 4 presents the conclusions of this study and discusses their relevance.

2. Observational Programme

2.1. Observations and Data Reduction

The 0.5-m telescope, Cousins R filter and 'STAR I' CCD camera of the Climenhaga Observatory of the University of Victoria (Robb & Honkanen, 1992) were used for the photometric observations. APM 08279+5255's apparent brightness makes it an ideal extragalactic target for such a telescope. At a redshift of 3.911, the R-band filter encompasses Ly_α λ1216 and N V λ1240, as well as weak emission of Si+O λ1400, with C IV λ1909 occurring in the red tail of the filter [see Figure 1 of Irwin et al. (1998)]. The prominent emission lines are strongly absorbed from both self-absorption and strong broad absorption line features, and the dominant flux in the band is continuum emission from the quasar.

Using standard IRAF[8] routines, the frames were bias subtracted, flat-fielded, and the magni-

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tudes were derived from 6″ apertures using the "Centroid" centering option of the PHOT package [see Robb et al. (1997) for more details of the reduction procedure]. Due to the small field of view, extinction effects are negligible and no corrections have been made for them. Also, no corrections were applied to transform the R-band magnitudes to a standard system.

The field around APM 08279+5255 is shown in Figure 1. In addition to the quasar, several prominent stars are apparent. Differential magnitudes were calculated by comparison with a bright 'standard' star labelled **S2**. The automatic observing procedure exposed a number of images of the field, between 2 and 100, over a night, dependent upon weather conditions. Typically ~ 50 frames, each with an integration time of 222 sec, were thereby obtained. The photometric data in each of the 23 nights for which data was procured was examined for brightness variations that might have occurred during the night, but no significant variations could be attributed to any of the targets. The fields acquired in a single night of observing were, therefore, combined.

2.2. Results

Differential magnitudes with respect to **S2** were calculated for APM 08279+5255 and the other stars labelled in the Figure 1. These results are tabulated in Table 1 and are presented graphically in Figure 2. To improve clarity, the light curves in this figure have been offset from their original values. An examination of the light curves for the brighter stars in the field, specifically **S1**, **S2** and **S4**, reveals that they have remained constant over the observing period. This also appears to be the case for **S3**, although it does possess several systematic variations that suggest variability.

The mean and standard deviation of these nightly means was found to be 3.928 ± 0.023 for **S1**-**S2**. This standard deviation assures us that both the stars **S1** and **S2** are not variable at this level of precision. Comparing APM 08279+5255 to **S2**, however, the overall differential magnitude was found to be 3.997 ± 0.068, suggesting that significant variability took place during the course of our monitoring campaign.

This is very apparent on examination of the light curves with the most dramatic systematic change in any light curve occurring in APM08-**S2**. While initially remaining constant at the start of the observing period, at Day 1230 it begins to brighten, with an increase of ~ 0.2 mag by the final observation.

3. Variability

What is the source of the observed variability in APM 08279+5255? Two possibilities immediately present themselves, each with different consequences for our understanding of this gravitationally lensed, ultraluminous system.

3.1. Intrinsic Variability

While some quasars show spectacular multi-wavelength variability on short timescales [e.g. Optically-Violent Variables (Webb et al. 1990) and Intra-Day Variables (Kedziora-Chudczer et al. 1997)], all quasars are seen to vary by some degree and several groups have employed a variability selection criterion to successfully identify samples of quasars (Hawkins & Veron 1993). Thought to arise in variable accretion rates and disk instabilities in the central regions of the quasar nucleus, several studies of the characteristics of quasar variability have been undertaken in recent years (Di Clemente et al. 1996; Cristiani et al. 1996; Scholz, Meusinger & Irwin 1997; Cristiani et al. 1997; Giveon et al. 1999) with the goal of unraveling the structure at the core of quasars [c.f. Aretxaga, Cid Fernandes & Terlevich (1997)]. Hook et al. (1994) considered a sample of three hundred quasars over an extended baseline of several years and found that, while the amplitude of quasar variability appears not to be a function of redshift, there is an inverse trend of the amplitude of the variability with the absolute magnitude of the quasar. Considering the scatter in their relation, however, the observed variability in APM 08279+5255 is quite consistent with it being intrinsic to the quasar.

3.2. Gravitational Microlensing

Given the small image separation, the light from APM 08279+5255 must pass through the inner regions of the lensing galaxy where the optical depth to microlensing can be substantial. Unlike the simple single or binary star microlensing seen in the Galactic halo (Alcock et al. 1993), microlensing in this regime results in complex light curves which are characterized by regions of high magnification variability, interspaced with quiescent periods of demagnification (Kayser, Refsdal & Stabell 1986). Could the observed variability be due to such microlensing?

The quintessential example of a microlensed quasar is the quadruply imaged Q2237+0305 which, with over a decade of monitoring, has reveal microlensing variations of up to 0.3 mag in a matter of weeks (Corrigan et al. 1991; Østensen et al. 1996). Comparing the light curves of the two systems and noting that, given the relative gravitational lensing geometry, the time scale of microlensing events should be $\sim 4\times$ longer than those seen in Q2237+0305 (a value which is reasonably insensitive to the assumed cosmology), the observed rise is also consistent with the microlensing hypothesis.

4. Discussion

This paper has presented the results of a year of monitoring the gravitationally lensed, ultra-luminous broad absorption line quasar APM 08279+5255. Photometry relative to several stars in the field reveals that, in the latter months of these observations, APM 08279+5255 has brightened by ~ 0.2 magnitudes. There are two potential causes for the source of this variability; either this

high redshift quasar source is being microlensed by stars in a foreground galaxy, or the variability is intrinsic to the quasar source. Both hypotheses are consistent with the current data and further photometric monitoring is required before the exact source of the variability can be determined.

Evidence for gravitational microlensing in APM 08279+5255 raises an interesting possibility. As discussed earlier, even accounting for the effects of macrolensing the luminosity of APM 08279+5255 is substantial and intrinsically it still ranks amongst the most luminous objects known. But could APM 08279+5255 be a 'normal' quasar that is undergoing an extreme gravitational microlensing magnification event? Two arguments suggest this is not the case:

- **Differential Lensing:** The degree to which a source is magnified is dependent upon its scale size, with small sources being more strongly magnified (Chang 1984). During the microlensing of quasars this results in the enhancement of only the continuum emission from the central accretion disk, with the emission from the more extended broad line region remaining unchanged [c.f. Lewis et al. (1998a)]. Similarly, in APM 08279+5255, while the quasar continuum flux could be enhanced by microlensing, the sub-mm/IR flux which arises in an extended dusty region will remain unchanged. Subject to only macrolensing effects, the inferred sub-mm/IR luminosity of APM 08279+5255 is a prodigious $\sim 10^{13}\,L_\odot$ (Ibata et al. 1999; Egami et al. 1999) and it remains intrinsically an extremely luminous object.

- **Statistical Considerations:** Microlensing is a stochastic process whose probability of magnification, μ, falls rapidly at high values ($p(\mu) \propto \mu^{-3} \quad \mu \gg 1$). Examining the high resolution images (Ibata et al. 1999; Egami et al. 1999), the two main images (A&B) are of very similar brightness, within 25% of each other. If we were (un)lucky enough to have caught APM 08279+5255 during a high magnification event, high enough to account for its apparent hyperluminous properties, is it possible that more than one image would be in such a state? If we assume that to be in this apparently ultraluminous state an image suffers a microlensing amplification of greater than ~ 100, then the probability of finding the second image also magnified by this factor is less than $\sim 10^{-8}$. Hence it is very unlikely that both images are simultaneously undergoing substantial microlensing enhancement.

We conclude, therefore, that while microlensing may account for the observed variability, it cannot play a dominant role in distorting our view. Intrinsically APM 08279+5255 must be an extremely luminous system.

The identification of variability in APM 08279+5255 can further help reveal the true nature of this complex system. High resolution images with both NICMOS on the Hubble Space Telescope (Ibata et al. 1999) and with the 10m Keck Telescope (Egami et al. 1999) clearly show that the two bright images identified in earlier observations are accompanied by a fainter image (designated C) located between them. While several arguments suggest that this is a third image of the high redshift quasar source, its location is suspiciously close to where one would expect to find the foreground lensing galaxy (Ibata et al. 1999). If the high redshift source is indeed variable, a high

spatial resolution monitoring program would clearly reveal whether C also varies in step with the other images (subject to a gravitational lens time delay), revealing it to truly be a third image, or the lensing galaxy. This procedure would also determine the degree of microlensing in each of the individual images.

While current observations are unable to fully constrain the gravitational lensing geometry in APM 08279+5255, the simple image configuration suggests that the dominant mass along the line of sight is a single, isolated galaxy (Ibata et al. 1999; Egami et al. 1999). Further observations, such as deep imaging of the field around APM 08279+5255, will refine this picture as it will allow an accurate model for the lensing potential to be determined. A variable source and a simple gravitational lensing geometry suggests that APM 08279+5255 may represent one of the few 'golden' gravitational lenses from which cosmological parameters can be derived from time delay measurements between the various images (Williams & Schecter 1997; Lovell et al. 1998). APM 08279+5255 is clearly an ideal subject for a high resolution monitoring campaign.

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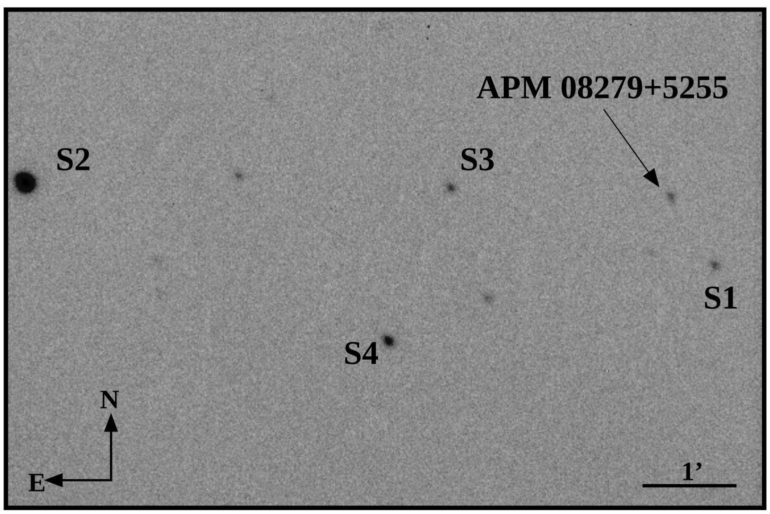

Fig. 1.— The observed field of APM 08279+5255 as observed in the R-band by the 0.5m telescope of the Climenhaga Observatory at the University of Victoria. As well as the quasar, several comparison stars are marked; **S1** is close to APM 08279+5255 and is of similar brightness, while **S2** is considerably brighter than APM 08279+5255, allowing for more precise photometry. Two other stars which are employed in the photometric analysis (**S3** & **S4**) are also denoted.

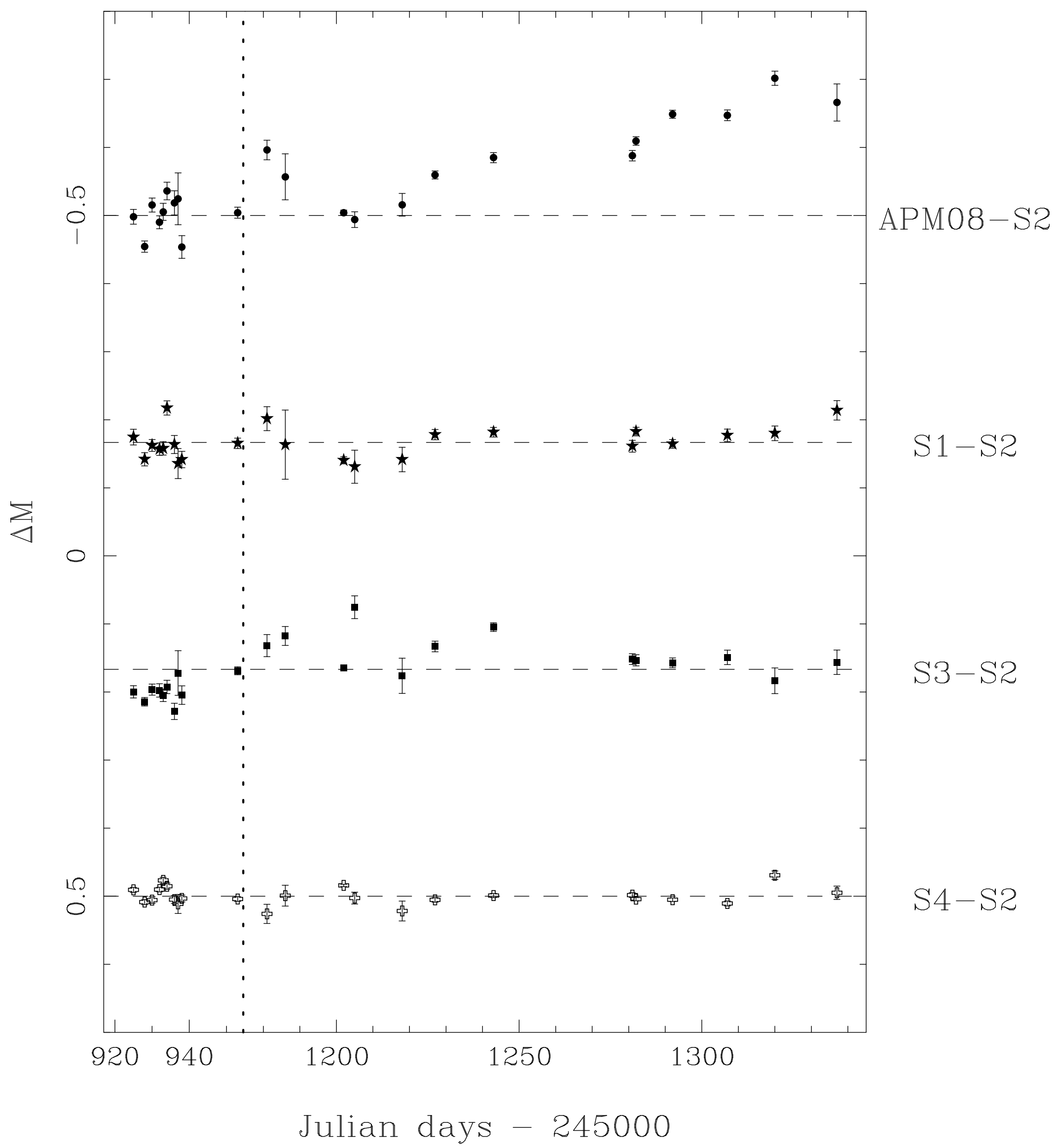

Fig. 2.— The differential R-Band light curves of the objects denoted in Figure 1 as compared to the bright star **S2**. The light curves have been offset to improve clarity. For each light curve the offsets are; (APM08-**S2**,-4.548), (**S1-S2**,-4.095), (**S3-S2**,-3.648) & (**S4-S2**,-2.405). The error bars represent the uncertainty in the mean value of combining a single night of data, and the vertical line delineates the two observing seasons.

Table 1. Summary of the differential R-band photometry

Date	N_{frame}	**APM08-S2**	**S1-S2**	**S3-S2**	**S4-S2**
925	56	4.049 ± 0.011	3.920 ± 0.012	3.847 ± 0.009	2.896 ± 0.004
928	79	4.093 ± 0.008	3.953 ± 0.010	3.862 ± 0.006	2.914 ± 0.004
930	87	4.032 ± 0.010	3.932 ± 0.009	3.844 ± 0.008	2.911 ± 0.005
932	48	4.057 ± 0.009	3.938 ± 0.009	3.845 ± 0.010	2.896 ± 0.004
933	33	4.042 ± 0.013	3.937 ± 0.010	3.852 ± 0.009	2.882 ± 0.005
934	74	4.012 ± 0.013	3.877 ± 0.010	3.840 ± 0.010	2.891 ± 0.005
936	68	4.029 ± 0.018	3.931 ± 0.013	3.876 ± 0.012	2.910 ± 0.006
937	9	4.023 ± 0.038	3.959 ± 0.022	3.820 ± 0.033	2.917 ± 0.014
938	20	4.094 ± 0.017	3.953 ± 0.012	3.852 ± 0.014	2.909 ± 0.005
953	66	4.043 ± 0.008	3.929 ± 0.008	3.816 ± 0.006	2.909 ± 0.003
1181	18	3.951 ± 0.014	3.893 ± 0.018	3.779 ± 0.016	2.931 ± 0.014
1186	2	3.991 ± 0.034	3.931 ± 0.051	3.765 ± 0.014	2.905 ± 0.015
1202	101	4.043 ± 0.004	3.954 ± 0.005	3.812 ± 0.003	2.889 ± 0.002
1205	13	4.054 ± 0.011	3.964 ± 0.024	3.723 ± 0.017	2.908 ± 0.009
1218	10	4.032 ± 0.017	3.953 ± 0.018	3.824 ± 0.026	2.927 ± 0.015
1227	47	3.988 ± 0.006	3.916 ± 0.008	3.781 ± 0.008	2.911 ± 0.003
1243	48	3.963 ± 0.007	3.913 ± 0.007	3.752 ± 0.006	2.904 ± 0.003
1281	27	3.960 ± 0.008	3.933 ± 0.009	3.799 ± 0.008	2.904 ± 0.004
1282	93	3.938 ± 0.006	3.912 ± 0.006	3.801 ± 0.008	2.910 ± 0.003
1292	93	3.899 ± 0.006	3.930 ± 0.007	3.805 ± 0.007	2.910 ± 0.003
1307	70	3.900 ± 0.008	3.917 ± 0.009	3.797 ± 0.011	2.916 ± 0.004
1320	22	3.846 ± 0.010	3.914 ± 0.011	3.831 ± 0.019	2.875 ± 0.006
1337	29	3.881 ± 0.027	3.881 ± 0.014	3.804 ± 0.018	2.900 ± 0.010

Note. — Summary of the R-band differential magnitudes obtained on each of the objects denoted in Figure 1, with respect to the bright star **S2**. Here, the date of the observation is given in Julian Days - 245000, while N_{frame} is the number of images obtained that night. The errors represent the uncertainty in the mean of the combination of these frames.